

The $c\bar{c}$ Pentaquarks by a Quark Model

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Recent LHCb experiments have shown us that there are two resonances in the $J/\psi p$ channel in the Λ_b decay, whose spin and parity are most probably $(3/2^- \ 5/2^+)$. In this work, we investigate the $I(J^P) = \frac{1}{2}(\frac{1}{2}^-)$, $\frac{1}{2}(\frac{3}{2}^-)$, and $\frac{1}{2}(\frac{5}{2}^-)$ $uudc\bar{c}$ pentaquark states by employing the quark cluster model. It is found that the color-octet isospin- $\frac{1}{2}$ spin- $\frac{3}{2}$ uud configuration gives an attraction to such five-quark systems. This configuration together with the color-octet $c\bar{c}$ pair gives structures around the $\Sigma_c^{(*)}\bar{D}^{(*)}$ thresholds: one bound state, two resonances, and one large cusp are found in the $uudc\bar{c}$ negative parity channels. We argue that these resonances and cusp may correspond to, or combine to form, the negative parity pentaquark peak observed by LHCb.

KEYWORDS: hidden-charm pentaquark; color-octet baryon; exotic hadron; multiquark hadron; baryon-meson scattering

1. Introduction

In 2015, two candidates of the new exotic baryons, $P_c(4380)$ and $P_c(4450)$, had been reported by LHCb. They are observed in the $\Lambda_b^0 \rightarrow J/\psi p K^-$ decay. The $P_c(4380)$ has a mass of $4380 \pm 8 \pm 29$ MeV and a width of $205 \pm 18 \pm 86$ MeV while $P_c(4450)$ has a mass of $4449.8 \pm 1.7 \pm 2.5$ MeV and a width of $39 \pm 5 \pm 19$ MeV. The most favorable set of the spin parity for the lower and the higher peaks is $J^P = (\frac{3}{2}^-, \frac{5}{2}^+)$, but $(\frac{3}{2}^+, \frac{5}{2}^-)$ or $(\frac{5}{2}^+, \frac{3}{2}^-)$ are also acceptable according to their analysis [2]. Their configuration is considered to be $uudc\bar{c}$: a hidden-charm pentaquark of the isospin $\frac{1}{2}$.

In this work, we discuss the negative-parity $udsc\bar{c}$ pentaquarks [1]. They are considered to couple to baryon-meson states, and their feature is observed in the short range properties of such baryon-meson states. For this purpose, we employ the quark cluster model, which successfully explained the short range part of the baryon-baryon interaction and the structure of the light-flavored pentaquark $\Lambda(1405)$ [3,4]. Recent lattice QCD results are found to give similar short range potentials to those of the quark cluster model for the baryon-baryon interaction [5].

Let us first discuss possible configurations of uud quarks in the $uudc\bar{c}$ pentaquarks. These three light quarks can be color-singlet or color-octet. So, when the orbital configuration is totally symmetric, the uud configuration in the $uudc\bar{c}$ systems can be totally symmetric (**56**-plet) or mixed symmetric (**70**-plet) in the flavor-spin $SU_{f\sigma}(6)$ space accordingly. They are classified as:

$$\mathbf{56}_{f\sigma} = \mathbf{8}_f \times \mathbf{2}_\sigma + \mathbf{10}_f \times \mathbf{4}_\sigma, \quad \mathbf{70}_{f\sigma} = \mathbf{1}_f \times \mathbf{2}_\sigma + \mathbf{8}_f \times \mathbf{2}_\sigma + \mathbf{8}_f \times \mathbf{4}_\sigma + \mathbf{10}_f \times \mathbf{2}_\sigma. \quad (1)$$

The color-singlet uud systems correspond to the usual **56**-plet baryons, whereas the color-octet ones correspond to the **70**-plet systems. Since the present work concerns systems of the isospin $\frac{1}{2}$ and the strangeness zero, the configurations of the three light quarks correspond to one of the following three:

Table I. The classification of the isospin- $\frac{1}{2}$ negative parity $qqqc\bar{c}$ states. The uud spin (s_q), color (c), CMI of the five quark systems at the heavy quark limit ($\langle O_{\text{cmi}} \rangle_{5q}^{(HQ)}$), the possible five quark spin with the multiplicity (J), the lowest S -wave threshold (T) and the CMI contribution to the threshold energy ($\langle O_{\text{cmi}} \rangle_T^{(HQ)}$) are listed.

s_q	c	$\langle O_{\text{cmi}} \rangle_{s_q}^{(HQ)}$	J	T	$\langle O_{\text{cmi}} \rangle_{\text{T}}^{(HQ)}$
$[q^3 1 \frac{1}{2}]$	$\frac{1}{2}$	1	$-(\frac{1}{2})^2, \frac{3}{2}$	$N\eta_c, NJ/\psi$	-8
$[q^3 8 \frac{1}{2}]$	$\frac{1}{2}$	8	$-(\frac{1}{2})^2, \frac{3}{2}$	$\Lambda_c \overline{D}^{(*)}$	-8
$[q^3 8 \frac{3}{2}]$	$\frac{3}{2}$	8	$\frac{1}{2}, (\frac{3}{2})^2, \frac{5}{2}$	$\Sigma_c^{(*)} \overline{D}^{(*)}$	$\frac{8}{3}$

(a) color-singlet spin- $\frac{1}{2}$ baryon in $(\mathbf{8}_f \times \mathbf{2}_\sigma)$, namely, nucleon, (b) color-octet spin- $\frac{1}{2}$ q^3 in $(\mathbf{8}_f \times \mathbf{2}_\sigma)$, and (c) color-octet spin- $\frac{3}{2}$ q^3 in $(\mathbf{8}_f \times \mathbf{4}_\sigma)$. In the following, we denote each of them by $[q^3 1 \frac{1}{2}]$, $[q^3 8 \frac{1}{2}]$, and $[q^3 8 \frac{3}{2}]$, respectively. Since the spin of the $c\bar{c}$ pair is either 0 or 1, the total spin of the $uudc\bar{c}$ systems is either $\frac{1}{2}$ (5-fold), $\frac{3}{2}$ (4-fold), or $\frac{5}{2}$ (1-fold). (See Table I.)

In Table I, we list the color magnetic interaction (CMI) evaluated by the uud part of the five-quark system, ($\langle O_{\text{cmi}} \rangle_{5q}^{(HQ)}$), which corresponds to the CMI contribution to the five-quark system at the heavy quark limit. The lowest S -wave thresholds (T) are also shown together with the CMI contribution to the threshold energy ($\langle O_{\text{cmi}} \rangle_T^{(HQ)}$). As seen from the table, $\langle O_{\text{cmi}} \rangle_{5q}^{(HQ)}$ is smaller than $\langle O_{\text{cmi}} \rangle_T^{(HQ)}$ for the $[q^3 8 \frac{3}{2}]$ configuration; which means that CMI is attractive in this configuration. Since $uudc\bar{c}$ is color-singlet as a whole, the system of the color-octet uud with the color-octet $c\bar{c}$ can be observed as $\Lambda_c \bar{D}^{(*)}$ or $\Sigma_c^{(*)} \bar{D}^{(*)}$ baryon meson states, where each of the hadrons is color-singlet. The above CMI contribution is expected to be seen as an attraction in the $\Sigma_c^{(*)} \bar{D}^{(*)}$ baryon meson channels. We argue that this attraction may cause the one of the observed peaks by LHCb.

2. Model

The model Hamiltonian, H_q , consists of the central term, H_c , and the color spin term, V_{cmi} . The H_c consists of the kinetic term, K , the confinement term, V_{conf} , and the color Coulomb term, V_{coul} :

$$H_q = H_c + V_{\text{cmi}}, \quad H_c = K + V_{\text{conf}} + V_{\text{coul}}. \quad (2)$$

Both of the V_{coul} and V_{cmi} terms come from the effective one-gluon exchange interaction between the quarks.

The color flavor spin part of the q^3 or $q\bar{q}$ wave functions is taken as a conventional way [6]. The orbital wave function of the mesons, ϕ_M , and that of the baryons, ϕ_B , are written by Gaussian with a size parameter b , $\phi(\mathbf{r}, b)$:

$$\phi_M(\mathbf{r}_M) = \phi(\mathbf{r}_{12}, \frac{x_0}{\sqrt{\mu_{12}}}), \quad \phi_B(\mathbf{r}_B) = \phi(\mathbf{r}_{12}, \frac{x_0}{\sqrt{\mu_{12}}}) \phi(\mathbf{r}_{12-3}, \frac{x_0}{\sqrt{\mu_{12-3}}}), \quad (3)$$

where the reduced masses, μ_{12} and μ_{12-3} , correspond to the Jacobi coordinates, \mathbf{r}_{12} and \mathbf{r}_{12-3} . We assume that the size parameter of the orbital motion can be approximated by $b = x_0 / \sqrt{m}$ and minimize the central part of the Hamiltonian, H_c , against x_0 for each of the flavor sets: $u\bar{c}$, $c\bar{c}$, uud , udc . For the baryons, this means that the ratio of the size parameters is kept to a certain mass ratio; e.g., b_{uc}/b_{ud} in Λ_c or Σ_c is equal to $\sqrt{\mu_{ud}/\mu_{uc}}$.

We employ the resonating group method (RGM) in order to solve the five-quark systems. The wave function of the five quark system, Ψ , consists of the q^3 baryon and the $q\bar{q}$ meson with the relative

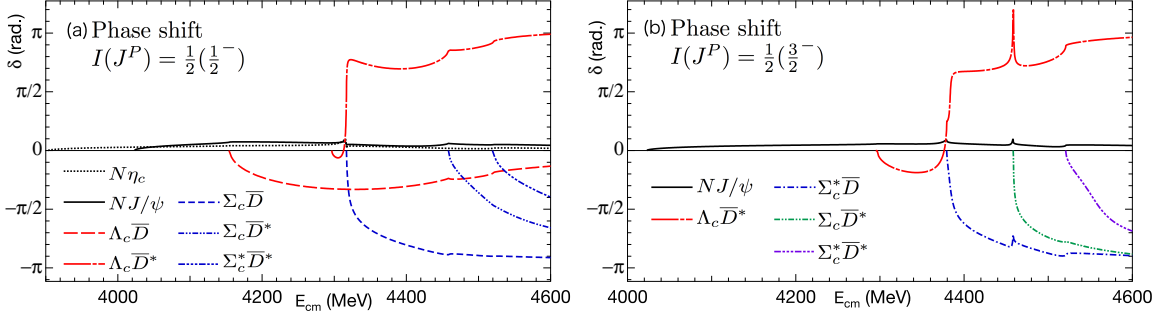


Fig. 1. The scattering phase shift of the S -wave $uudc\bar{c}$ $I(J^P)=\frac{1}{2}(\frac{1}{2}^-)$ channel (Fig. a) and that of the $\frac{1}{2}(\frac{3}{2}^-)$ channel (Fig. b). The solid line is that of the NJ/ψ channel, the dotted line the $N\eta_c$, the long-dashed and the long-dot-dashed lines are for $\Lambda_c\bar{D}$ and $\Lambda_c\bar{D}^*$, and the dashed, dot-dashed, double-dot-dashed, and triple-dot-dashed lines are for the $\Sigma_c\bar{D}$, $\Sigma_c^*\bar{D}$, $\Sigma_c\bar{D}^*$, and $\Sigma_c^*\bar{D}^*$, respectively. Figures are taken from ref. [1]. (color online)

wave function χ [3, 4]:

$$\Psi = \sum_{\nu} c^{\nu} \mathcal{A}_q \{ \psi_B^{\nu}(\mathbf{r}_B) \psi_M^{\nu}(\mathbf{r}_M) \chi^{\nu}(\mathbf{R}) \}, \quad (4)$$

where \mathcal{A}_q stands for the quark antisymmetrization which operates on the four quarks, and ν for the baryon-meson channel. By integrating out the internal wave function of the hadrons, the RGM equation can be obtained from the equation of motion for the quarks, $(H_q - E)\Psi = 0$, as

$$\sum_{\nu'} \int (H^{\nu\nu'} - EN^{\nu\nu'}) \chi^{\nu'} = 0, \quad (5)$$

where $H^{\nu\nu'}$ and $N^{\nu\nu'}$ are the hamiltonian and the normalization kernels.

In order to investigate the nature of the resonance states as well as the bound states, We define a three-body operator, \mathcal{P}^{cs} , to extract the uud color c , spin s_q , orbital $(0s)^3$ component:

$$\mathcal{P}^{csq} = \mathcal{P}_{123}^{csq} + \mathcal{P}_{124}^{csq} + \mathcal{P}_{134}^{csq} + \mathcal{P}_{234}^{csq} \quad (6)$$

$$\mathcal{P}_{ijk}^{csq} = |uud; cs_q(0s)^3\rangle \langle uud; cs_q(0s)^3| \quad (7)$$

$$\langle \mathcal{P}^{csq} \rangle = \sum_{\nu\nu'} \int \prod d\mathbf{r} \{ \psi_b^{\nu} \psi_m^{\nu} \chi^{\nu} \}^{\dagger} \sum_{ijk} \mathcal{P}_{ijk}^{csq} \mathcal{A}_q \{ \psi_b^{\nu'} \psi_m^{\nu'} \chi^{\nu'} \}. \quad (8)$$

3. Results

It is found that a very shallow bound state appears in the $\Sigma_c^*\bar{D}^*$ $J = \frac{5}{2}$ system, in which the uud is in the $[q^3 8\frac{3}{2}]$ configuration. As seen from the scattering phase shifts shown in Figs. 1 (a) and (b), there is one sharp resonance in the $\Lambda_c\bar{D}^*$ channel of the $J = \frac{1}{2}$ system, while one sharp resonance and one strong cusp are found in the $\Lambda_c\bar{D}^*$ channel of the $J = \frac{3}{2}$ system. The number of these structures, one in $J = \frac{1}{2}$, two in $\frac{3}{2}$, one in $\frac{5}{2}$, corresponds exactly to the number of the multiplicity for the $[q^3 8\frac{3}{2}]$ configuration shown in Table 1.

The $\langle \mathcal{P}^{cs} \rangle$'s are shown in Figs. 2 (a) and (b). The size of $[q^3 8\frac{3}{2}]$ configuration enhances at the resonance or the cusp energies. This feature is more clearly found in the $J = \frac{3}{2}$ system. There, the attraction originally forms a bound state each in the $\Sigma_c^*\bar{D}$ and in the $\Sigma_c\bar{D}^*$, which become a resonance and a cusp in the $\Lambda_c\bar{D}^*$ channel by the channel coupling. At these resonance and cusp energies, the

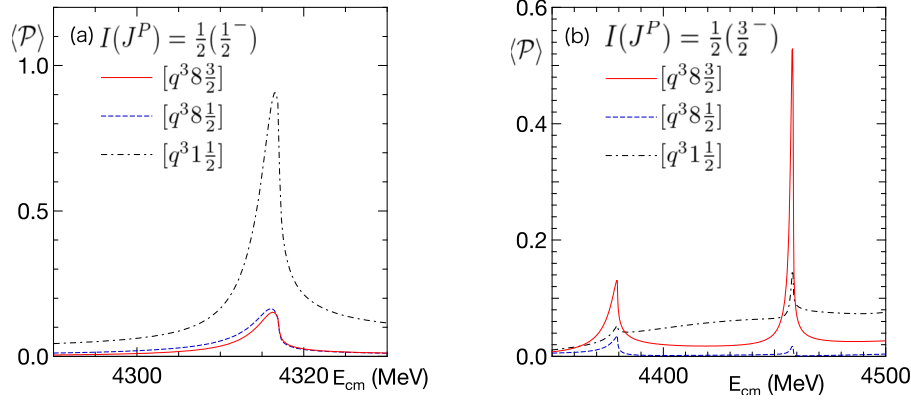


Fig. 2. The factor $\langle \mathcal{P} \rangle$ to find the $uud(0s)^3$ configuration in the scattering wave function with the initial NJ/ψ channel in the S -wave $uudc\bar{c}$ $I(J^P)=\frac{1}{2}(\frac{1}{2}^-)$ channel (Fig. a) and that of the $\frac{1}{2}(\frac{3}{2}^-)$ channel (Fig. b). The solid line stands for the factor to find in the color octet spin $\frac{3}{2}$, the dashed line for the color-octet spin $\frac{1}{2}$, and the dot-dashed line for the color singlet spin $\frac{1}{2}$. (color online)

short range part of the wave function enhances and the proportion of $[q^3 8 \frac{3}{2}]$ also enhances. These resonance and cusp indeed have the $[q^3 8 \frac{3}{2}]$ configuration at the short range part. As for the $J = \frac{1}{2}$ system, the size of this configuration is much smaller than that of the $\frac{3}{2}$ system. Without the coupling to the $\Lambda_c \bar{D}$ channel, however, the resonance becomes a bound state of the $\Sigma_c \bar{D}$ channel, and the $[q^3 8 \frac{3}{2}]$ component is 0.7 of the whole $uud(0s)^3$ component of that bound state. This configuration plays an important role to make the resonance also for the $J = \frac{1}{2}$ system though the mixing of the $\Lambda_c \bar{D}$ channel reduces its size. The above situation shows us that $[q^3 8 \frac{3}{2}]$, the uud color-octet spin $\frac{3}{2}$ configuration, which may be called as a ‘color-octet uud baryon,’ causes these resonances.

In order to compare our results to the experimental spectra, it will be necessary to include the effects of the meson-exchange in the long range baryon-meson interaction. We would like to argue, however, these resonances and cusp may correspond to, or combine to form, the negative parity pentaquark peak observed by LHCb.

4. Summary

The $I(J^P) = \frac{1}{2}(\frac{1}{2}^-)$, $\frac{1}{2}(\frac{3}{2}^-)$, and $\frac{1}{2}(\frac{5}{2}^-)$ $uudc\bar{c}$ systems are investigated by the quark cluster model. It is shown that the color-octet isospin- $\frac{1}{2}$ spin- $\frac{3}{2}$ uud configuration gains attraction from the color magnetic interaction. The $uudc\bar{c}$ states with this configuration cause structures around the $\Sigma_c^{(*)} \bar{D}^{(*)}$ thresholds. We have found one bound state in $\frac{1}{2}(\frac{5}{2}^-)$, one resonance and a cusp in $\frac{1}{2}(\frac{3}{2}^-)$, and one resonance in $\frac{1}{2}(\frac{1}{2}^-)$ in the negative parity channels, which may be the origin of the negative parity P_c peak observed in the Λ_b decay.

References

- [1] A part of this work has been discussed in S. Takeuchi and M. Takizawa, arXiv:1608.05475 [hep-ph].
- [2] R. Aaij *et al.* [LHCb Collaboration], Phys. Rev. Lett. **115**, 072001 (2015).
- [3] M. Oka, K. Shimizu and K. Yazaki, Prog. Theor. Phys. Suppl. **137**, 1 (2000).
- [4] S. Takeuchi and K. Shimizu, Phys. Rev. C **76**, 035204 (2007).
- [5] K. Sasaki *et al.* [HAL QCD Collaboration], Prog. Theor. Exp. Phys. **2015**, 113B01 (2015).
- [6] See, for example, K. A. Olive *et al.* [Particle Data Group Collaboration], Chin. Phys. C **38**, 090001 (2014).
- [7] Y. Yamaguchi and E. Santopinto, arXiv:1606.08330 [hep-ph].